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ONBORD (On-board Navigation of Ballistic ORDnance): Gun-Launched Munitions Flight Controller

by Michael J. Wilson, Rex A. Hall, and Mark Ilg

ARL-TR-3210 August 2004

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14. ABSTRACT

On-board navigation of ballistic ordnance (ONBORD) is a digital flight control system with telemetry support designed for the guidance, navigation, and control of gun-launched munitions. Requirements such as low cost, small size, low power, and high-g survivability, which exclude traditional flight controllers, are satisfied by the ONBORD system. The electronics consist of a single 1.4-inch printed circuit board that includes the Texas Instruments TMS320F2812 digital signal processor whose microcontroller-like capabilities reduce the amount of peripheral circuitry necessary for flight control interfaces. This report describes the hardware and software that comprise ONBORD, including design constraints, available interfaces to navigation and control hardware, and software operation.

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1. Introduction

A guidance, navigation, and control (GN&C) system is a critical component of any smart weapon. The development of smart munitions will benefit greatly from an appropriate general purpose, fully programmable GN&C system. This report introduces ONBORD (on-board navigation of ballistic ordnance) digital flight control electronics and software for gun-launched munitions. The system consists of a single 1.4-inch diameter circular printed circuit board (PCB) with a digital signal processor (DSP), the associated support electronics, input/output (I/O) interfacing capabilities, and flight control software (see figure 1). Requirements such as low cost, small size, low power, and high-g survivability exclude traditional flight controllers and have driven the design of ONBORD.

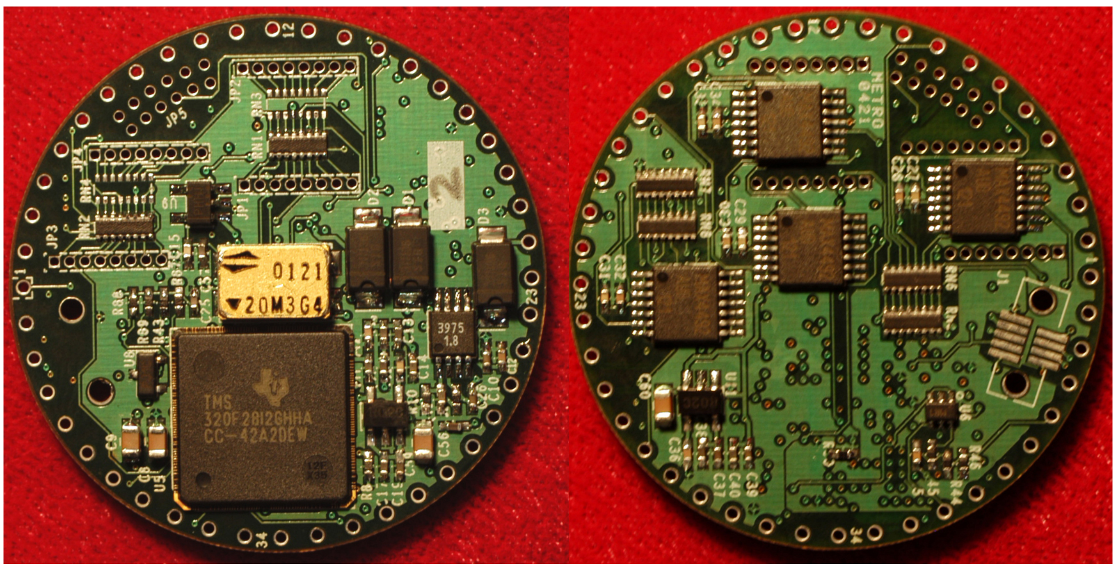

Figure 1. ONBORD flight controller, top (left), bottom (right).

At the heart of the ONBORD system is the Texas Instruments 150-megahertz (MHz) TMS320F2812 DSP. This processor is an ideal choice for a flight control system because of the variety of input and output peripherals. A fully programmable 16-channel, 12-bit analog-to-digital converter (ADC) is included, which can operate at sampling rates as fast as 12.5 megasamples per second (MSPS). This ADC is ideal for converting sensor input for devices such as magnetometers, accelerometers, and angular rate sensors that are used for measuring flight dynamics. Serial ports, including synchronous and asynchronous types, provide interfaces to other critical GN&C components such as a global positioning system (GPS) receiver or seeker. The event manager modules include general purpose timers, full-compare/pulse width modulation (PWM) units, capture units, and quadrature-encoder pulse (QEP) circuits ideal for controlling motors connected

to canards. Also, built-in flash memory is capable of storing the required code for a flight controller.

The complex board layout is highly motivated by the requirements for gun-launched munitions. "Power-up" circuits ensure correct timing sequences for DSP boot-up while occupying minimal board space. Several novel interface connectors provide access to sensors, motors, other navigation hardware, and "on-the-fly" programming with a notebook computer. ONBORD can also be mated with a signal conditioning board to provide anti-aliasing filters for ADC.

ONBORD software package performs sensor data acquisition, flight parameter estimation, canard motor control, and telemetry. Calibration data are used to convert sensor values to engineering units. Flight parameters are then estimated via sensor data. These parameters are used to determine appropriate control sequences to motors connected to canards. For test and evaluation applications, telemetry of sensor data, GPS receiver data, estimated parameters, and control instructions is necessary to determine performance. ONBORD can provide telemetry data streams to an on-board transmitter in the desired format. The software is stored in the flash memory of the F2812 and begins execution when the power is turned on.

2. ONBORD Hardware

2.1 Design Requirements

The ONBORD PCB presented a number of challenges, with the size limitation being the most formidable. In most applications, the area reserved for the F2812 DSP and all related hardware exceeds 16 in^2. Fewer than 2 in^2 were available for ONBORD. With Spectrum Digital's eZdsp[1] (*1*) as a starting point and eliminating all hardware and DSP functions impertinent to this application, the miniature board would need the DSP, voltage regulation, power-up sequencing, programming interface, motor control interface, PCM output drivers, and anti-aliasing filters.

The PCB shape was designed to mate with the U.S. Army Research Laboratory (ARL) inertial sensor suite (ISS) PCB, as shown in figure 2. A stack containing the ISS, ONBORD, and a battery connector is shown in figure 3. This configuration is appropriately sized to fit within an aeroballistic diagnostic fuze body (see figure 4) or a 40-millimeter (mm) medium caliber munition.

[1] eZdsp™ is a trademark of Spectrum Digital.

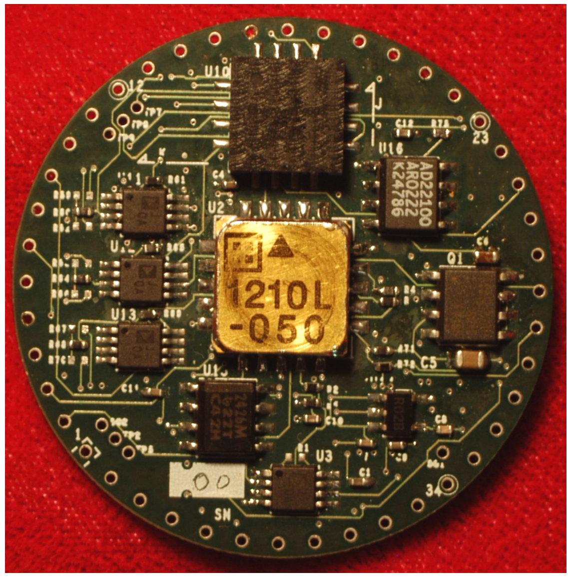

Figure 2. ARL 1.4-inch ISS, top view.

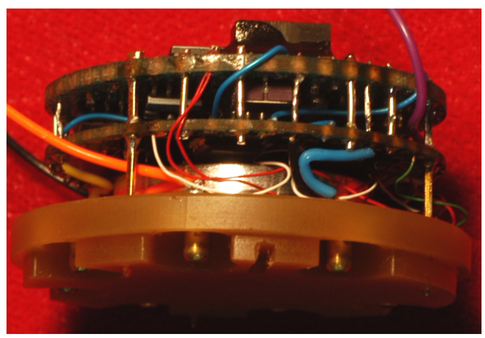

Figure 3. Stack with ISS and ONBORD.

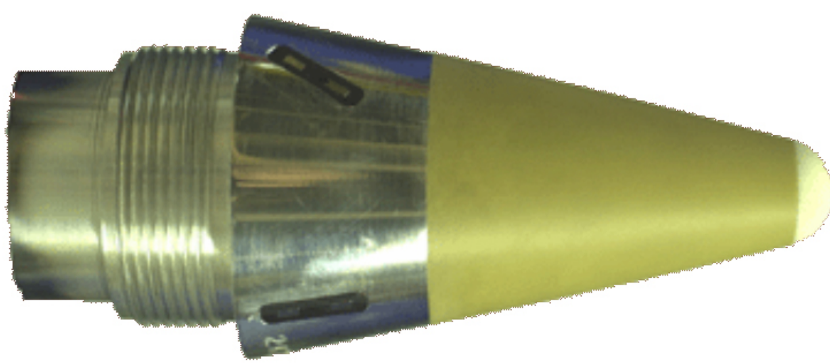

Figure 4. Fuze with ONBORD stack.

2.2 Clocking and Voltage Regulation

The F2812 requires very little external hardware support. All necessary oscillator-clocking signals are derived via an internal phase locked loop (PLL) from a single external Statek HGXO type clock oscillator. These oscillators have been used successfully in the high-g environment on several gun-launched projectiles in components such as the M/A-COM telemetry modulation unit (TMU)-003 transmitter. Input power regulation is provided by four low dropout linear voltage regulators. Analog circuitry and digital I/O are powered by separate 3.3-volt regulators, each with its own dedicated power plane within the PCB stack. The DSP core and external oscillator are also powered by individual 1.8-volt regulators; however, only the core has a dedicated internal plane. In accord the manufacturer's specifications, analog and digital grounds are tied together with a 0-ohm (Ω) resistor on the bottom of the PCB, under the center of the F2812.

2.2 Power-Up Sequencing

The DSP requires a very specific power-up sequence for which there are many dedicated central processing unit (CPU) power supervisory circuits available commercially off the shelf. All these require more area than is available on the ONBORD PCB. Therefore, power sequencing is accomplished by the incorporation of regulators with built-in enable functions. The rise and fall time of the enable pin voltage on each regulator is set via an resister-capacitor (RC) network. This network turns the appropriate regulator on or off at the correct time in the sequence. Power-on reset is accomplished by a miniature reset generator integrated circuit (IC) that applies the CPU external reset 180 milliseconds (ms) after input power is applied. Figure 5 illustrates the power-up sequence.

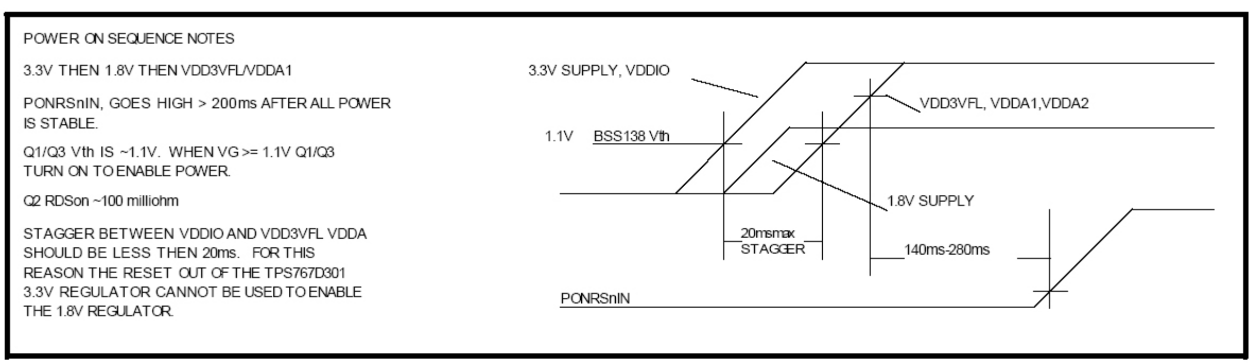

Figure 5. TMS320F2812 power-up sequence.

2.3 Interfaces

In order to program the DSP and use it to control flight hardware, two external interfaces were provided. Programming is accomplished through the F2812 Joint Test Action Group (JTAG) port, which requires seven connections. A Tyco nine-pin nanoconnector with 1-inch straight

leads was customized to fit the application and mounted to the underside of the PCB (see figure 6). The leads are formed with a bending fixture fabricated in house, shown in figure 7.

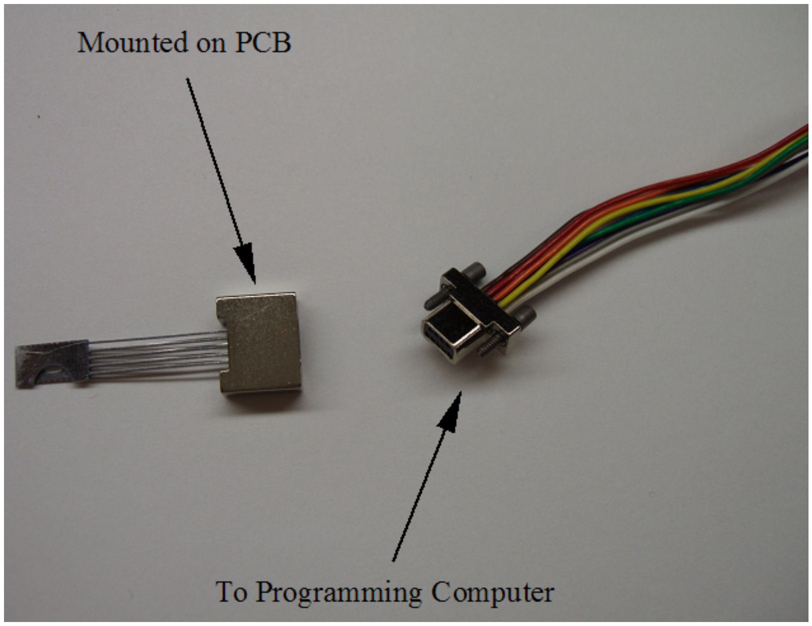

Figure 6. JTAG mini connector.

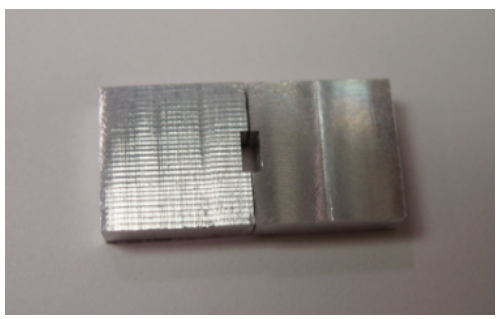

Figure 7. Lead bending fixture.

The motor control interface is simply two rows of six small plated through-holes that provide access to the I/O pins necessary to provide direction, speed, acceleration, and feedback information to and from the motors.

2.4 Input Scaling and Anti-Aliasing Filters and Pre-Modulation Filter

Sensor signals that range from 0 to 5 volts from the ARL 1.4-inch ISS are fed to the board on 16 of the 44 pins on the perimeter of the card (see figure 2). The DSP's ADC operates from the 3.3-volt supply; therefore, the I/O range is limited to 3.3 volts. All 16 channels are scaled through resistor dividers and buffered with low impedance drivers before the ADC input. The drivers reduce settling time and overall system distortion. The output of the ADC buffers can be directed straight to the on-board ADC or to an anti-aliasing "daughter" card by miniature 0-Ω

jumper packs. A four-pole Bessel filter is provided on the daughter card for each of the 16 data channels, and it can be stacked on the DSP card via two interfaces or bypassed, depending on which set of 0-Ω resisters is installed (see figure 8).

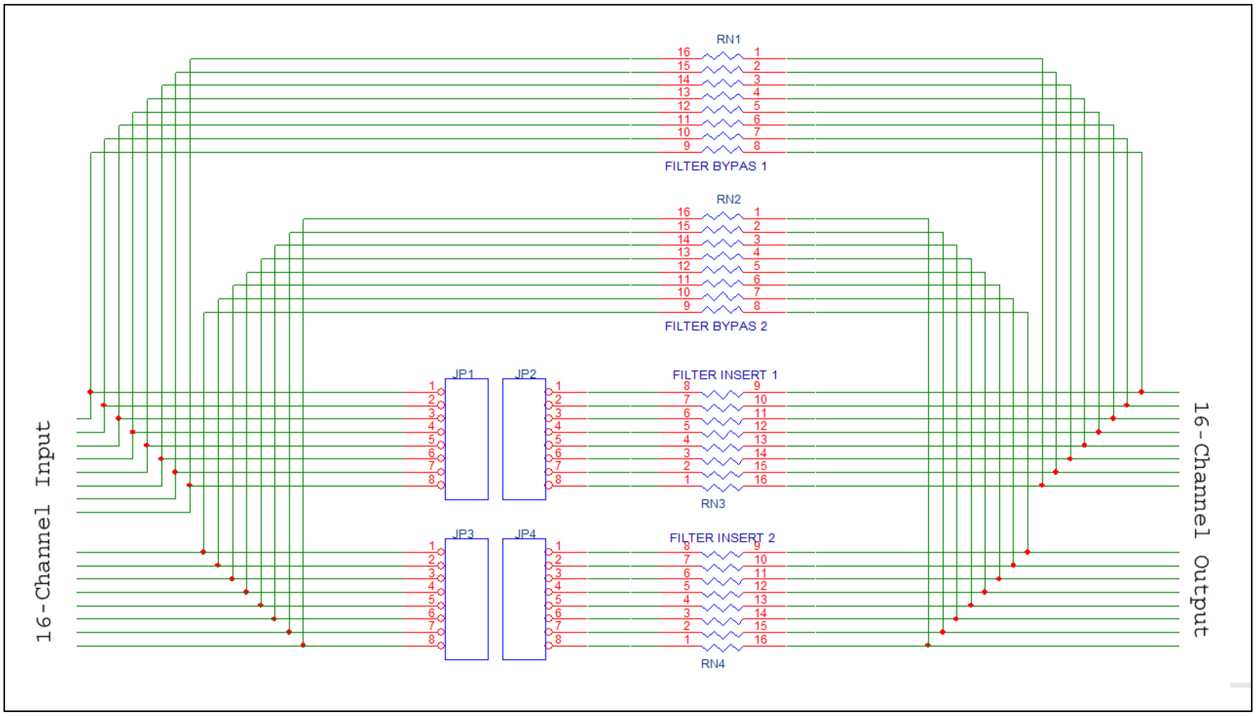

Figure 8. Anti-aliasing filter insert/bypass.

The DSP outputs a pulse code modulated (PCM) serial signal whose format and bit rate can be changed in software via the JTAG interface. Two high speed, high current buffered outputs are provided. One is a transistor-transistor logic (TTL) level signal capable of directly driving a bit synchronizer; the other is low pass filtered and level shifted in order to drive a telemetry transmitter.

3.   ONBORD Software

This section describes the current software available for the ONBORD system. The software has three primary functions: flight parameter estimation, canard motor control, and telemetry. Figure 9 gives the high level interactions between each software module and the hardware. Each module is described in detail.

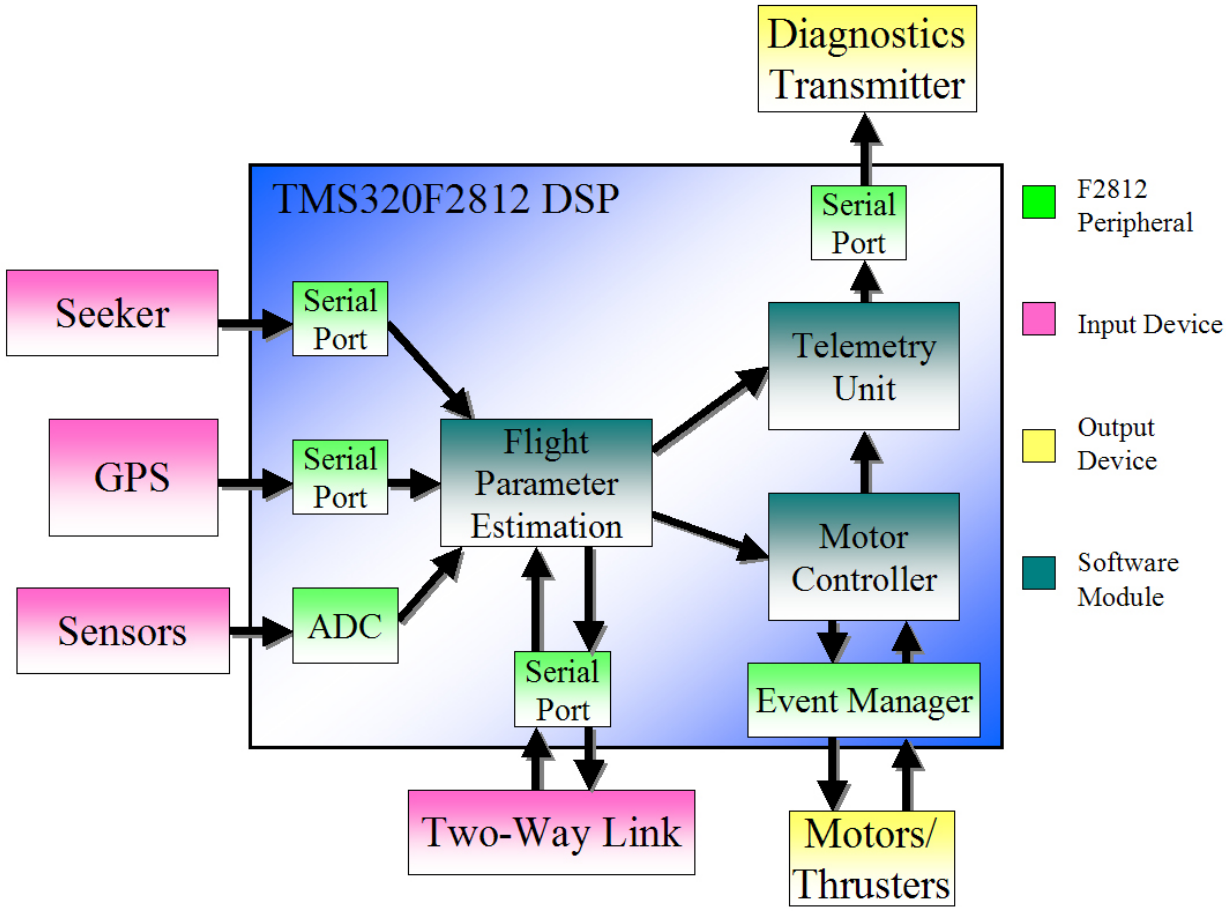

Figure 9. High level software module and hardware interactions.

3.1 Flight Parameter Estimation

In order to navigate and guide, it is necessary to estimate the projectile's state via the flight parameters of interest. Various sensors on the ISS board can be interfaced to the ADC on the F2812. ADC results are processed with calibration data to produce values in engineering units. The computed measurements can then be combined to derive different flight parameters in software on the DSP.

3.1.1 Attitude Estimates

ISS sensors such as magnetometers, accelerometers, and angular rate sensors are especially useful for attitude estimates. Therefore, this is the first capability developed for ONBORD. An attitude determination algorithm (*2*) has been implemented, which finds all three Euler angles describing a projectile's orientation via magnetometers and angular rate sensors. This algorithm is highly efficient, requiring only a few additions, multiplications, and trigonometric functions that use Texas Instruments (TI) IQmath (*1*) library for floating point arithmetic and trigonometric tables pre-programmed in the F2812's read-only memory. A projectile's spin rate can also be

found by ISS sensors. Frequency estimates of sine waves produced by radially oriented magnetometers are used in conjunction with the accelerometer ring to provide accurate spin rate determination.

3.1.2 Extensions

Software extensions are possible to complete ONBORD as a fully independent GN&C system. Two possibilities exist for navigation. The first uses an on-board GPS receiver to provide position information that could be used to navigate. The second uses a seeker to find a target relative to the projectile. Both methods would clearly rely on the attitude estimates described previously. Alternatively, navigational control can be conducted on the ground via a two-way communications link interfaced through a serial port. This link could also provide dynamic retargeting for the projectile. Generic interfaces to the F2812 have been established so that these navigational devices could be connected. Software upgrades would be used to handle the data processing.

3.2 Canard Motor Control

The F2812 DSP is optimized for motor control by a combination of the DSP with power electronics; controlling a motor is achieved with a properly designed controller. This section describes the DSP's ability to control a motor through the hardware and software and gives some detail of controller design implementation.

3.2.1 Motor Input

Motors are driven by the PWM output of the F2812, by which there is no need for expensive digital-to-analog converter circuits. PWM is ideal for H-bridge circuits that interface to conventional DC motors and brushless DC motors. The PWM output can interface to a step motor driver using only one PWM output and a direction signal, thus reducing the number of output lines between components. PWM can be configured with the event manager modules (EMMs): EVA, EVB (*1*). The frequency is controlled by the corresponding timer; the resolution is controlled by the timer period; and the duty cycle can be configured via the compare registers. Each EMM has six PWM outputs (three duty cycle independent) that would allow for multiple motor configurations.

3.2.2 Software Control

TI has reliable software algorithms that use several types of feedback for control (*1*). Feedback control is enabled by a digital encoder on the motor connected to the QEP input or via available ADC channels. The availability of two separate QEP circuits, each with two channels plus index, allows for the control of two independent motors.

Since the F2812 can be configured for multiple interruptions, control of the system can be properly timed. The EMMs allow for an interruption to be triggered by the capture input pins of the QEP circuit; otherwise, the QEP is tied directly to the timer. Interruptions are also driven by a CPU clock overflow to allow for time-dependent events that are critical for the control loop operation. Coupling the timer interruption and the QEP circuit, proper speed and/or position measurements are obtained with a fully digital control loop.

3.2.3 Rapid Prototyping

Control algorithms can be developed via MathWorks/Embedded Target for TI C2000™ DSP or VisSim[2]/Embedded Controls Developer for TI-C2000. Both programs allow GUI development and simulation of motor control systems with little or no external programming. This allows rapid prototyping and testing of control loops. Along with rapid prototyping control systems, MathWorks/Link for Code Composer Studio allows for complete control of the DSP parameters in a MATLAB[3] environment. This helps aid development of more optimized solutions to the control of different motor types.

3.2 Telemetry

Current telemetry data acquisition systems available for purchase and throughout U.S. Department of Defense test ranges use PCM/frequency modulation (PCM/FM). ONBORD has built-in hardware and software for PCM/FM telemetry systems. This enables test and evaluation of the performance of ONBORD in a new application by making all the relevant sensor and control data available for receiving.

To generate a PCM/FM signal, a serial bit stream is filtered and used as the input to an FM transmitter. ONBORD is capable of generating a custom bit stream to fit the application and output that bit stream on a synchronous serial port. For a detailed description of PCM/FM telemetry systems, see reference (*3*). Custom programming permits various binary encoding schemes. Buffering ensures that data are continuously transmitting so that a receiver does not need to repeatedly lock onto the signal.

4. Summary

The features and functionality of the ONBORD flight controller have been described. The system is a fully programmable unit that meets the requirement for gun-launched munitions. ONBORD's hardware provides substantial interfacing and filtering capability in addition to

[2]VisSim™ is a trademark of Visual Solutions, Inc.
[3]MATLAB®is a registered trademark of The MathWorks.

primary DSP support hardware. ONBORD's software provides sensor data acquisition, flight parameter estimation, motor control, and telemetry support. ONBORD will be continually improved to meet requirements for specific munitions and dynamic models.

4. Recommendations

As stated in section 3.1.2, a GPS receiver or seeker, with the associated support software, must be a future development for ONBORD to provide a complete flight controller. Additional processing power may also be required for high degree-of-freedom dynamic models. If this is the case, a high-performance DSP from TI's C6000 series can be interfaced with the F2812. The F2812 would maintain control over the system with its interfacing capabilities while the additional processor could be given specific processing tasks.

5. References

1. For all references regarding the TMS320F2812 and associated support software, see http://focus.ti.com/docs/prod/folders/print/tms320r2812.html.

2. Wilson, M.J. *Attitude Determination With Magnetometers for Gun-Launch Munitions*; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, in press.

3. Carden, F.; Jedlicka, R.; Henry, R. *Telemetry Systems Engineering*, Artech House: Norwood, MA, 2002.

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Appendix A. Pin Assignments for the 44-pin Perimeter Interface

This appendix provides the pin assignments for the 44-pin perimeter interface, the motor control interface, the JTAG programming interface and the anti-aliasing filter interface/bypass. Figure A-1 shows the locations of the interfaces on the board. Figure A-2 shows the pin locations for the JTAG and motor control interfaces. Figure A-3 shows the JTAG interface pin connection to the F2812. Figure A-4 shows the motor control interface pin assignments. Table A-1 lists the 44-pin perimeter interface pin assignments.

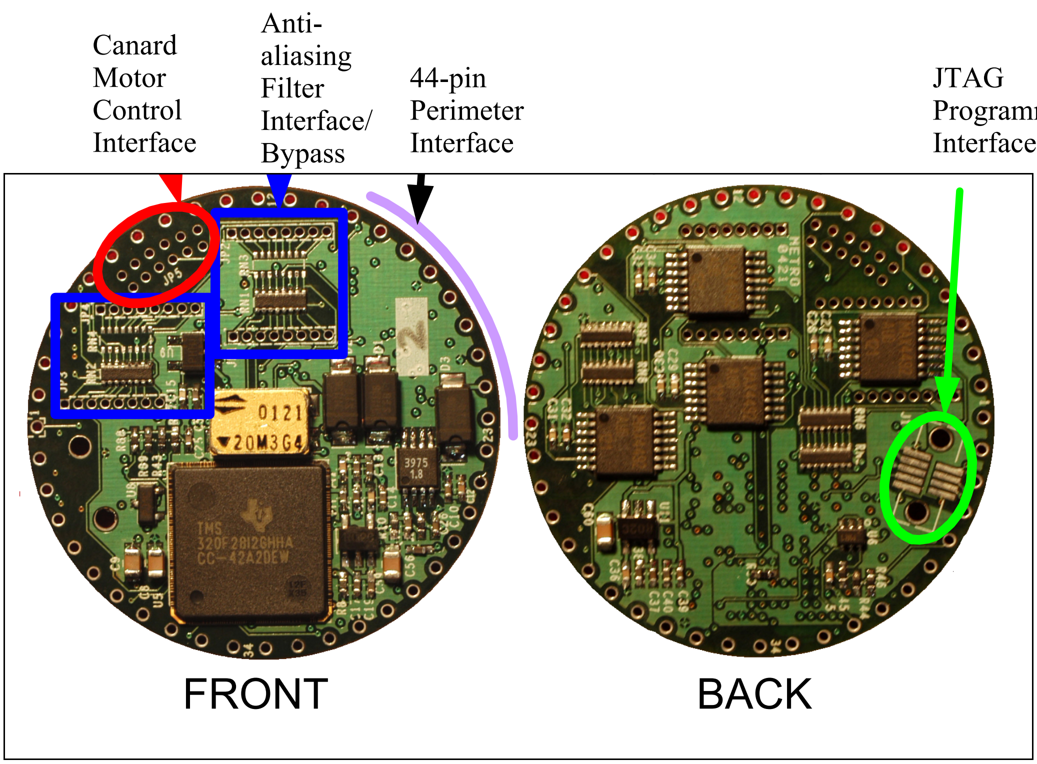

Figure A-1. ONBORD's interfaces.

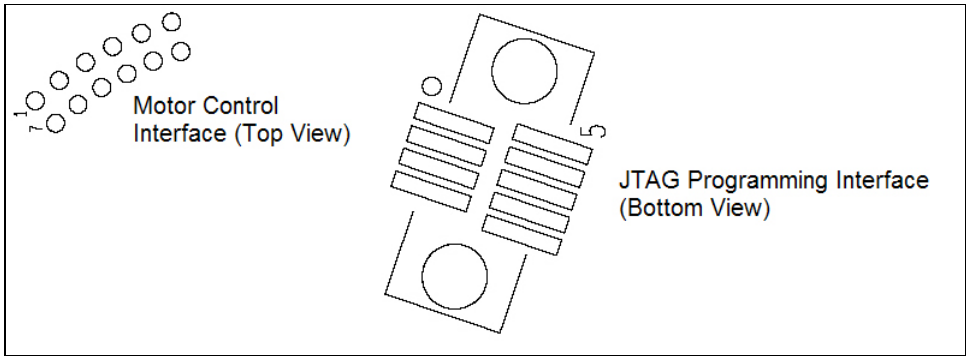

Figure A-2. Pin locations for the motor control interface (left) and JTAG programming interface (right).

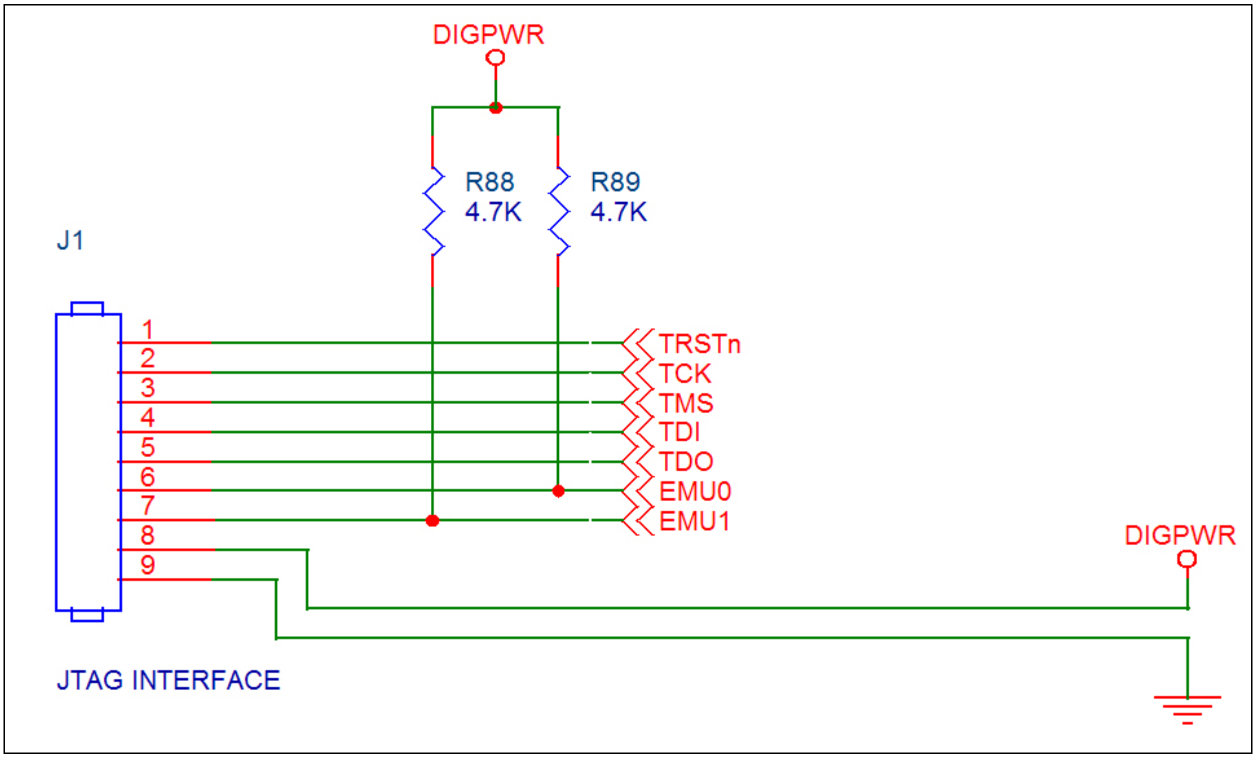

Figure A-3. JTAG interface connections to F2812.

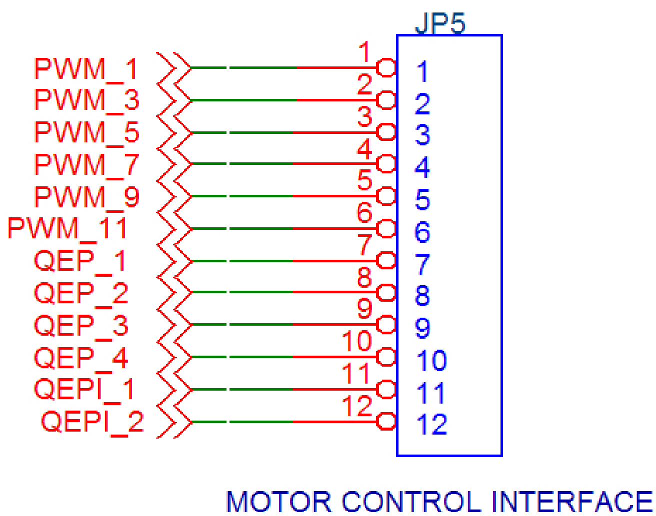

Figure A-4. Motor control interface pin assignments.

Table A-1. Pin assignments for 44-pin perimeter interface.

Pin	Function	F2812 Pin Correspondence
1	Analog Channel 0	ADC A0
2	Digital I/O	GPIO B7
3	Analog Channel 5	ADC A5
4	Analog Channel 14	ADC B6
5	Ground	
6	Analog Channel 15	ADC B7
7	Analog Channel 9	ADC B1
8	External Interrupt 1	XINT1
9	Analog Channel 2	ADC A2
10	Analog Channel 6	ADC A6
11		
12	ADC Start-of-Conversion Output	EVASOC
13		
14	ADC Start-of-Conversion Output	EVBSOC
15	ADC Start-of-Conversion Input	ADCSOC
16	8 V Input, Stack Power (STACKPWR)	
17	Analog Channel 12	ADC B4
18	Analog Channel 1	ADC A1
19	External Interrupt 13	XINT13
20	Analog Channel 3	ADC A3
21	Analog Channel 10	ADC B2
22	4 V Input, CREPWRIN	
23	McBSP Data Receive	MDRA
24	McBSP Data Transmit	MDXA
25	McBSP Receive Clock	MCLKRA
26	McBSP Transmit Clock	MCLKXA
27	McBSP Receive Frame Sync	MFSRA
28	Analog Channel 13	ADC B5
29	Analog Channel 4	ADC A4
30	Analog Channel 11	ADC B3
31	Analog Channel 8	ADC B0
32		
33	SCI B Transmit	SCITXDB
34	SCI B Receive	SCIRXDB
35	Timer 2 Compare	T2, CMP
36	Timer 1 Compare	T1, CMP
37	PCM TTL Output	
38	SPI A Clock	SPICLKA
39	SPI Master Input	SPISOMIA
40	External Clock Out	XCLKOUT
41	PCM Modulation Output	
42	SCI A Transmit	SCITXDA
43	SCI A Receive	SCIRXDA
44	Analog Channel 7	ADC A7

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G34 M HAMILTON S POMEROY
G34 S CHAPPELL G34 H MALIN
17320 DAHLGREN ROAD
DAHLGREN VA 22448-5100

3 CDR NAVAL SURF WARFARE CTR
ATTN G34 J LEONARD G34 W WORRELL
G34 M ENGEL
17320 DAHLGREN ROAD
DAHLGREN VA 22448-5100

4 CDR NAVAL SURF WARFARE CTR
ATTN G61 E LARACH G61 M KELLY
G61 A EVANS G5 D HAGEN
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